2003 Distributed Energy Resources Peer Review

December 4, 2003

Catalytica
ENERGY SYSTEMS

Component Development to Accelerate Commercial Implementation of Ultra-Low Emissions Catalytic Combustion

DEDICATED TO INNOVATIVE SOLUTIONS FOR CLEAN ENERGY PRODUCTION

Catalytica Energy Systems

- Mountain View, CA (R&D, Product Testing)
  - 55 employees, 30,000 square feet
  - Extensive laboratories and test facilities
  - 1.5 MW grid-connected gas turbine demonstration unit
- Gilbert, AZ (Manufacturing & Administration)
  - 35 employees, 40,000 square feet
  - Pilot production system operational
  - Commercial production system complete fall '02
  - Six Sigma & Lean Manufacturing processes
  - ISO 9000 certified

Gilbert, AZ facility

Project Plan

- Task 1.1: Cost Reduction – Catalyst Life Extension
- Task 1.2: Cost Reduction – Module Cost Reduction
- Task 2.1: Broadened Operating Range – Catalytic Secondary Burner
- Task 2.2: Broadened Operating Range – Catalytic Pilot for Lean Premix Burner
- Task 3.1: Diesel Fuel Conversion For Xonon

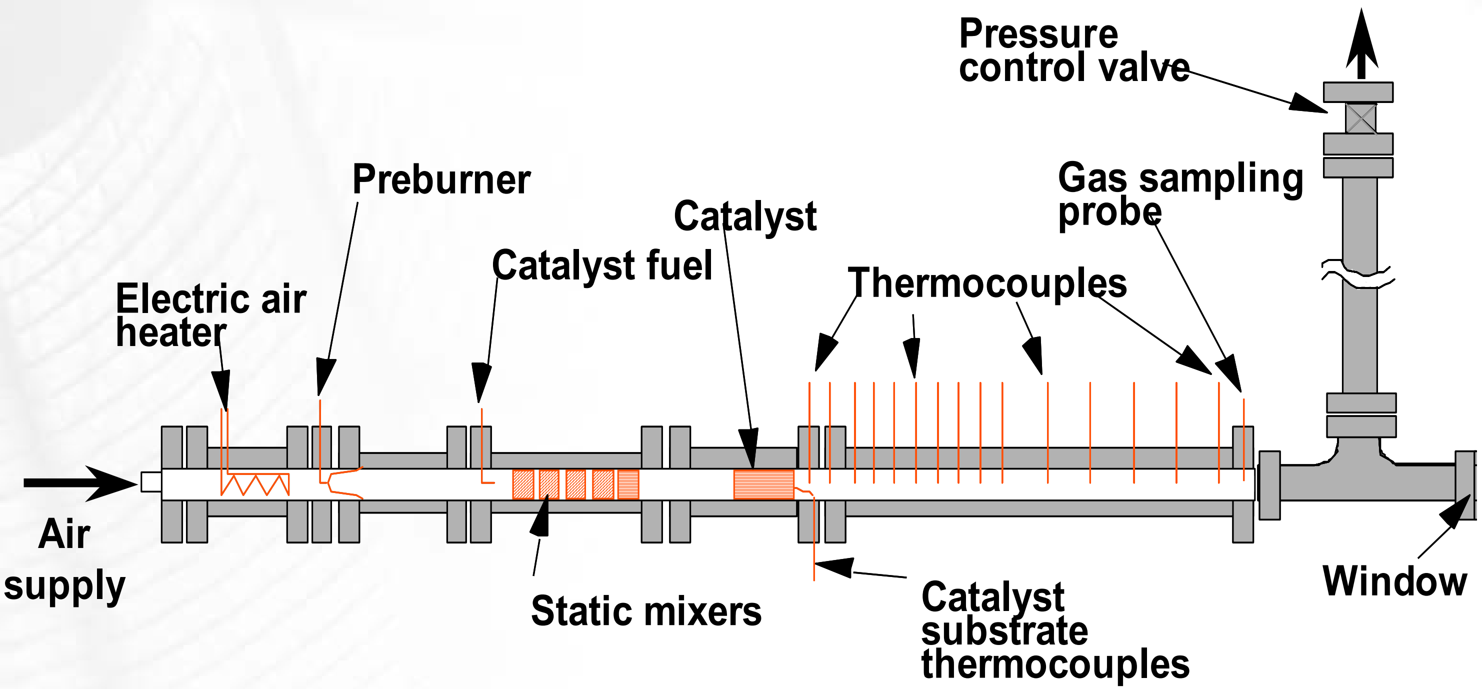
Project Plan

- Task 1.1: Cost Reduction – Catalyst Life Extension
  - Development of Generation 2.5 Pre-Aged Catalyst
  - Testing of Generation 3 Catalyst Materials Development
- Task 1.2: Cost Reduction – Module Cost Reduction
- Task 2.1: Broadened Operating Range – Catalytic Secondary Burner
- Task 2.2: Broadened Operating Range – Catalytic Pilot for Lean Premix Burner
- Task 3.1: Diesel Fuel Conversion For Xonon

Catalyst Life Extension
Sub-scale Commercial Test Reactor

View of one of CESI's two 2-in subscale catalyst module test reactors. These reactors are used for designing commercial-scale catalyst modules and for developmental testing.

Catalyst Life Extension
Sub-scale Commercial Test Reactor

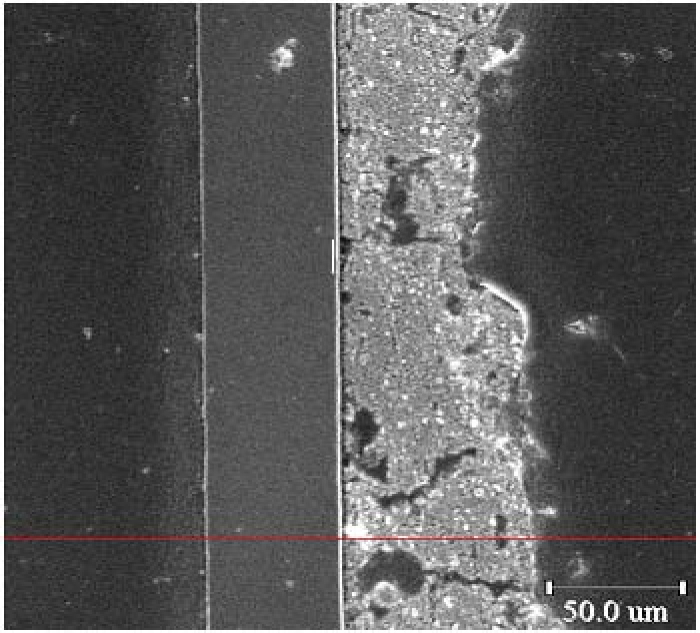


Schematic diagram of a subscale (2-in) catalyst module test reactor.

Catalyst Life Extension
Generation 2.5 Catalyst Development

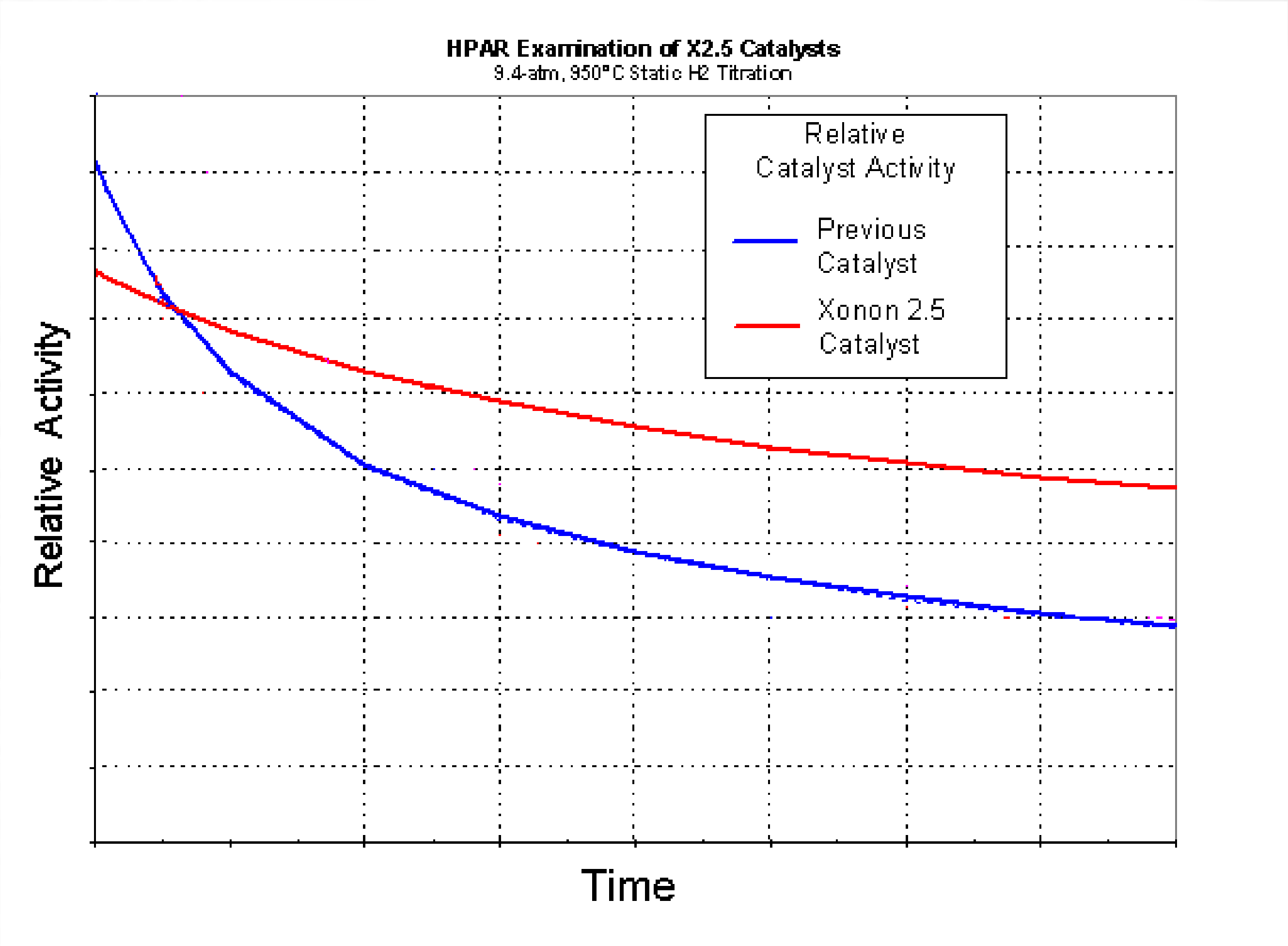
Generation 2.5 Catalyst Life Extension Goals

- Reduce sintering rate
- Improve combustion activity
- Improve cohesion
- Improve uniformity



Generation 2 Catalyst Section

Catalyst Life Extension
Advantage of Pre-Aged Catalyst



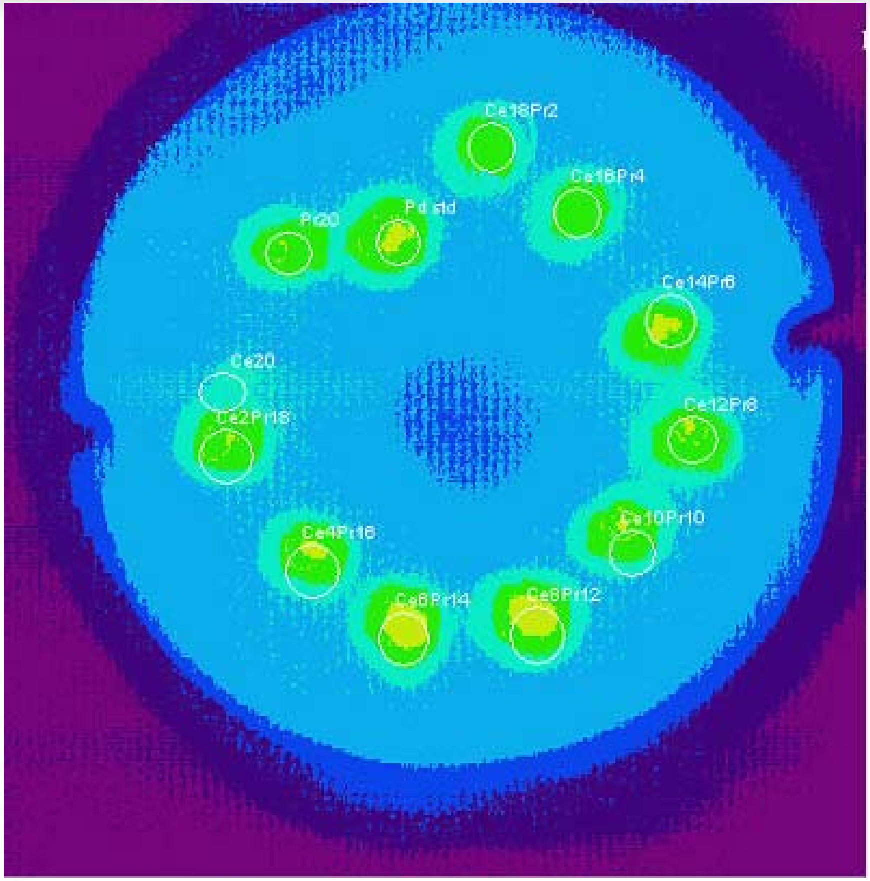
Catalyst Life Extension – Generation 2.5 Achievements

Catalyst Property	Gen 2.5 Target	Achieved 2000-2002	Future Development
Sintering Rate	Lower than Gen 2.0	Reduced by 50%	No plans – may be approaching limit
Combustion Activity	Comparable to Gen 2.0	Comparable to Gen 2.0	Reduce higher initial activity (24-hr)
Adhesion/ cohesion	Better than Gen 2.0	Increased by 100% (fresh)	Examine long-term cohesion (4000+hr)
Uniformity	Better than Gen 2.0	Improved (need metric)	Optimize slurry formulation

Catalyst Life Extension
Generation 3 Catalyst Development

- Multiple catalyst reactor successfully designed and used to screen Gen 3 materials
  - Uses thermal imaging method developed in-house for sub-scale test facility
  - Examined some 30 different promoted and supported solid-oxide catalysts
  - Activity comparable to supported Pd discovered for two base formulations
  - Two candidates optimized for further development

Catalyst Life Extension
Testing of Generation 3 Catalysts



Thermal Imaging Used To Rapidly Screen Candidate Catalyst Formulations

Catalyst Life Extension
Generation 3 Catalyst Development

- Additional work necessary for commercialization
  - Subscale tests in two stage catalyst system – preliminary design work
  - Aging (HPAR) tests conducted under accelerated conditions to 12,000-hr
    - Must examine operating temperature range to determine sintering rates
    - Must examine effect of gas composition and pressure on sintering rates
  - Develop powder production process and optimize washcoat slurry formulation

Project Plan

- Task 1.1: Cost Reduction – Catalyst Life Extension
- Task 1.2: Cost Reduction – Module Cost Reduction
  - Address cost of manufacturing and re-use costs for the container structure
  - Address durability and manufacturing cost of axial support structure
- Task 2.1: Broadened Operating Range – Catalytic Secondary Burner
- Task 2.2: Broadened Operating Range – Catalytic Pilot for Lean Premix Burner
- Task 3.1: Diesel Fuel Conversion For Xonon

Module Cost Reduction

- Design Considerations
  - Incorporate current product cost information
  - Design for low-volume start-up with ability to scale
  - Minimize first cost
  - Maximize re-use life
  - Design to resist creep and low cycle fatigue
  - Design

Module Cost Reduction

TFA Y-Joint Weld Process Improvement

Pre-Development

Post-Development

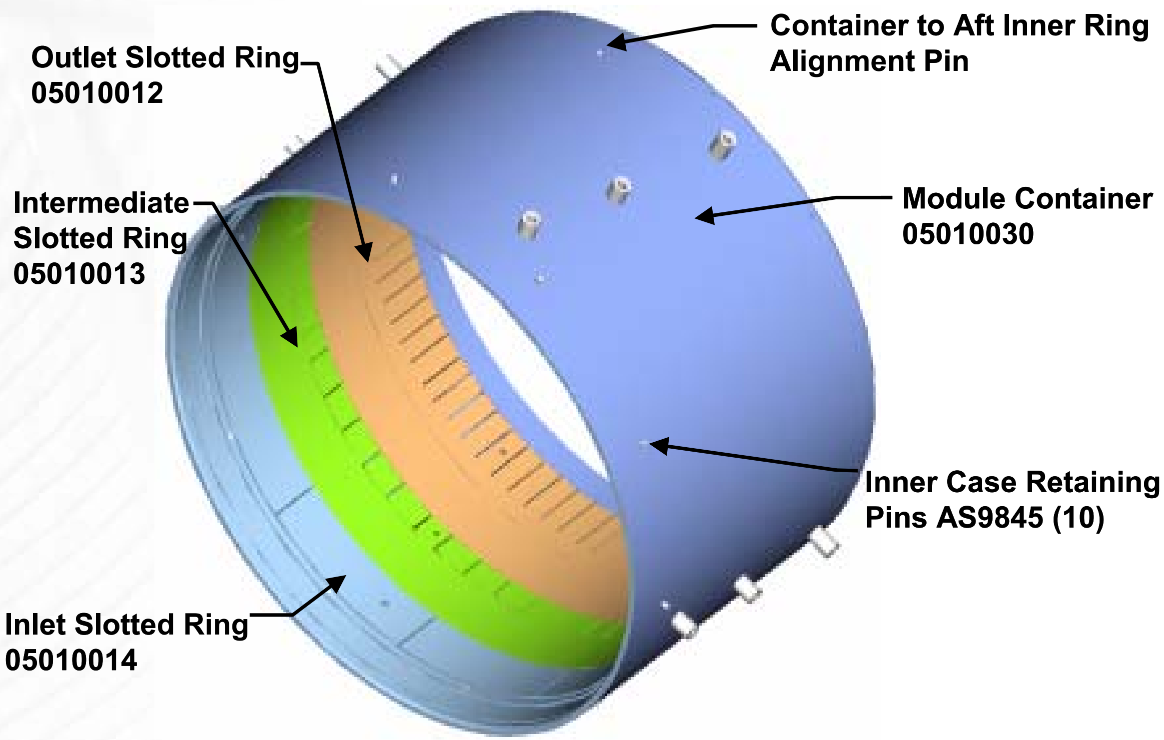
- Major Improvements penetration and uniformity
  - 10% increase in throat thickness
  - 25% decrease in SDev of process throughput
- Developed process control procedures and specification

Module Cost Reduction

Container Design Alternatives

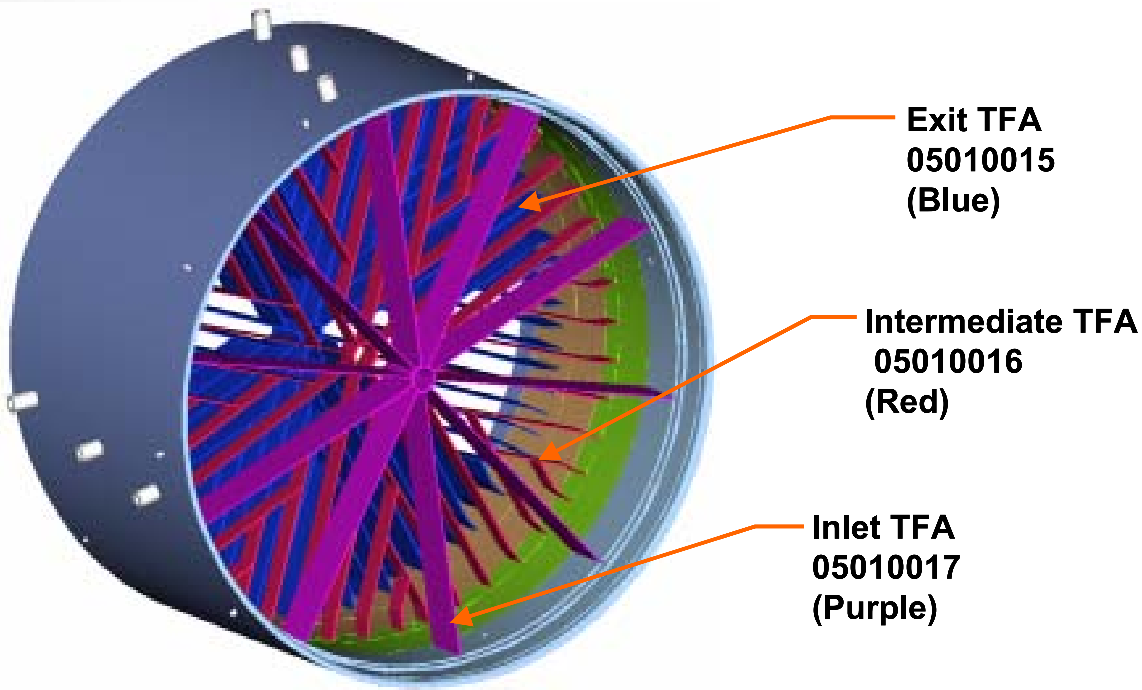
- Machined cast rings and welded can assembly
  - Most expensive assembly, high probability of distortion from circumferential welds and limited re-use life
- “Split-Can” two half cans with lengthwise flanges
  - Least expensive first cost, but has risks of leakage along bolted flange and possibly difficult to re-use
- Can-In-Can uses a machined cast outer shell with TFA supports and catalyst modules stacked inside
  - Best overall design with well understood processes, cost control, ease of assembly and dimensional stability

Module Cost Reduction



Container Slotted Ring Arrangement

Module Cost Reduction



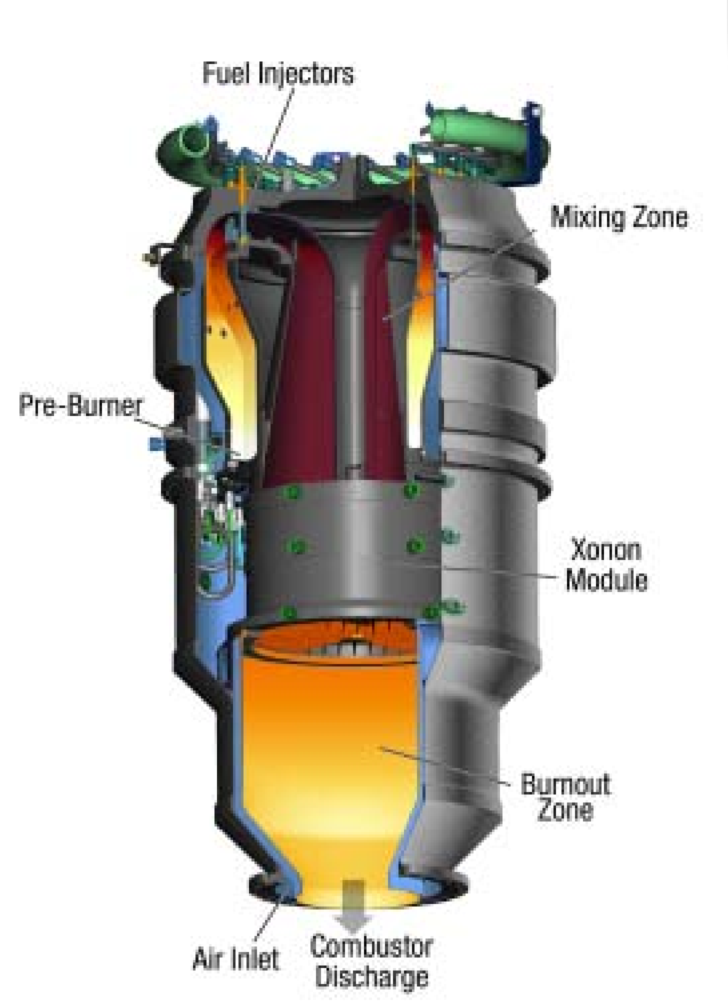
TFA Assembly Drawing

Project Plan

- Task 1.1: Cost Reduction – Catalyst Life Extension
- Task 1.2: Cost Reduction – Module Cost Reduction
- Task 2.1: Broadened Operating Range – Catalytic Secondary Burner
  - Develop a catalytic secondary module
  - Design burner flow path
- Task 2.2: Broadened Operating Range – Catalytic Pilot for Lean Premix Burner
- Task 3.1: Diesel Fuel Conversion For Xonon

Catalytic Secondary Burner

- General Arrangement
  - Air Inlet – Compressor Discharge
  - Preburner
  - Fuel Injector Array
  - Pre-Catalyst Mixing Zone
  - Xonon Module
  - Burnout Zone
  - Combustor Discharge

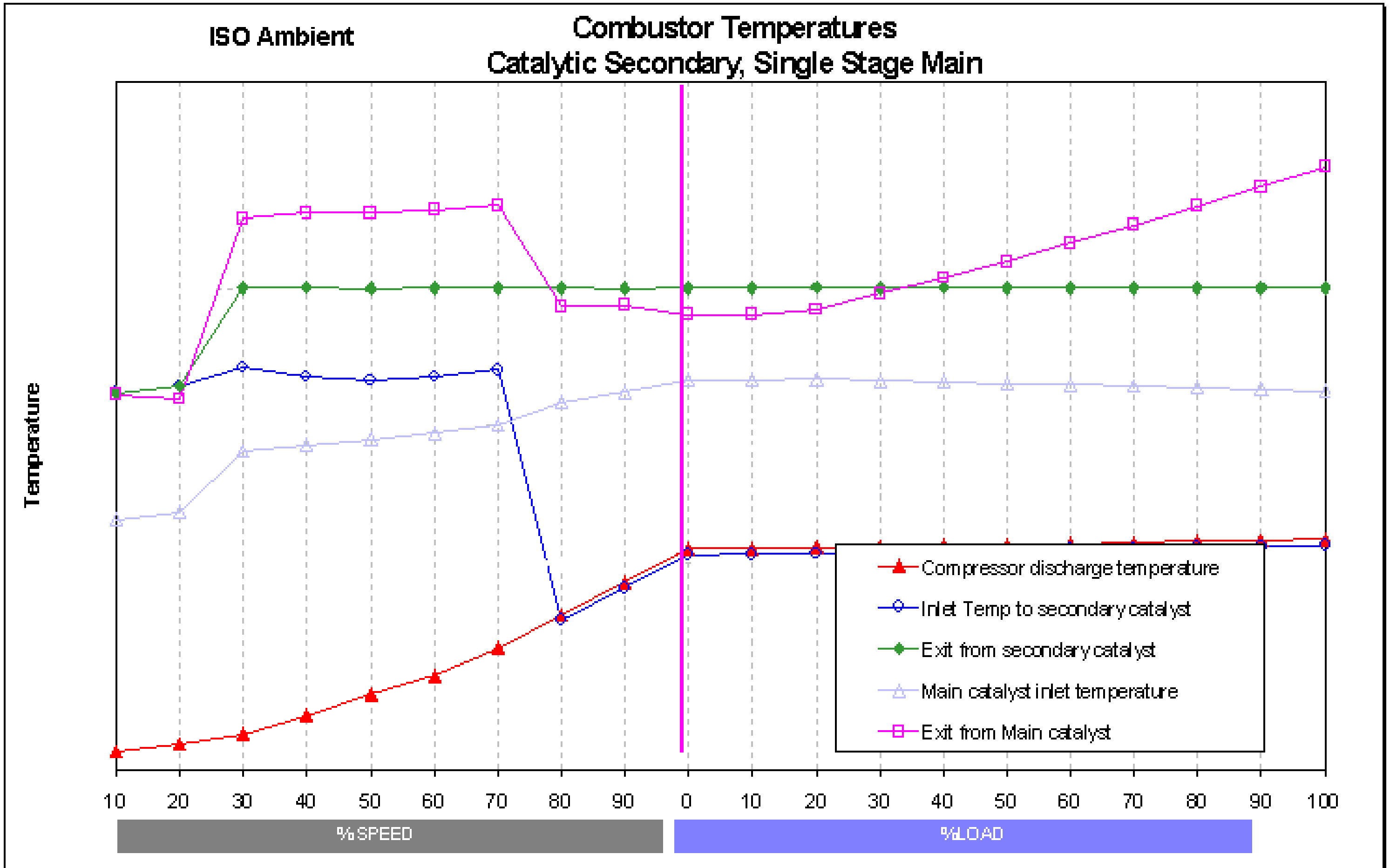


Catalytic Secondary Burner

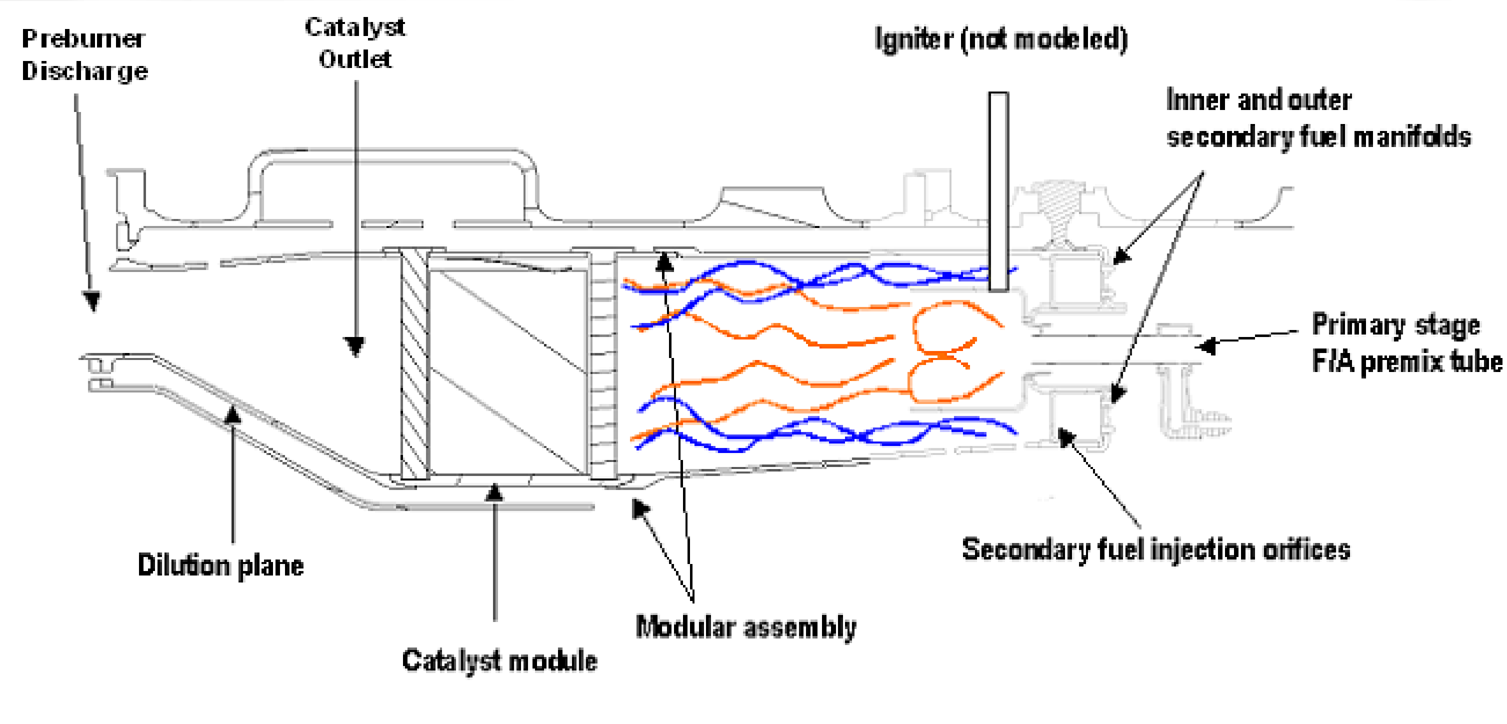
Operational Profile: Primary stage is used during start transient only. From FSNL to full load only secondary stage and main stage catalysts are fueled.

- Light off primary stage at low engine speed.
- Ramp up speed on starter with primary stage lit until secondary stage catalyst inlet exceeds light of temperature.
- Start fueling secondary stage catalyst. Fuel to a maximum catalyst outlet governed by life and performance criteria. Continue ramp.
- When CDT exceeds catalyst extinction temperature, fuel will be chopped to primary burner at which point it will flame out. Outlet temperature from the catalyst will be near constant.

Catalytic Secondary Burner



Catalytic Secondary Burner



Final concept from CFD analysis

Catalytic Secondary Burner

Development Status

- Catalytic preburner developed and refined with CFD
- Mechanical designs selected with analysis of critical parts

Future Work

- Perform detailed thermal growth analysis
- Evaluate required mixing and flow uniformity
- Refine operation profile for optimal life and performance

Project Plan

- Task 1.1: Cost Reduction – Catalyst Life Extension
- Task 1.2: Cost Reduction – Module Cost Reduction
- Task 2.1: Broadened Operating Range – Catalytic Secondary Burner
- Task 2.2: Broadened Operating Range – Catalytic Pilot for Lean Premix Burner
  - Rig Test Catalytic Pilot in Comparison to a Diffusion Pilot
  - Develop Conceptual Designs
- Task 3.1: Diesel Fuel Conversion For Xonon

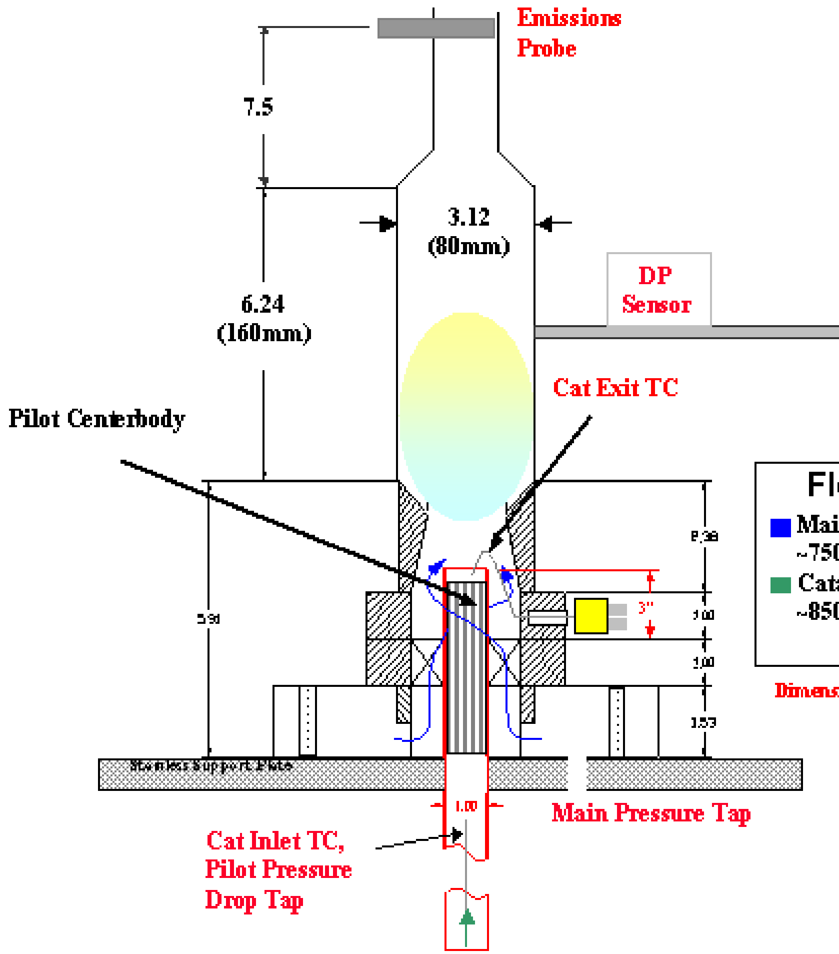
Catalytic Pilot For LPM Combustors

Increased Operating Range for Lean Pre-Mixed Combustors

Catalytic Pilot Features

- Replace diffusion pilot
- Assembled as center body of main injector
- Expected to increase operating range, reduce NOx and CO emissions, and reduce combustor dynamics

Catalytic Pilot
UCI Atmospheric Test Rig



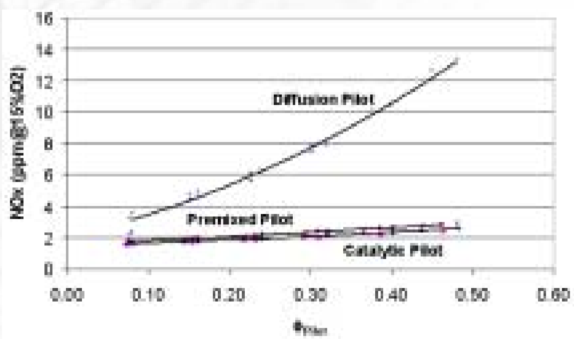
Flow Components

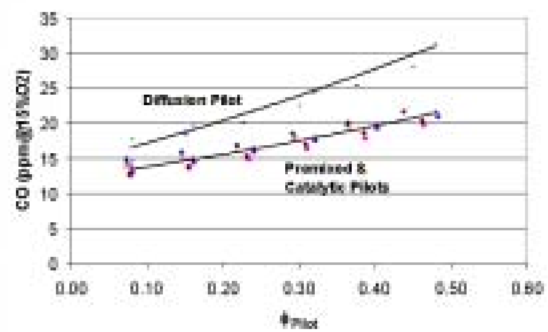
- Main Premixed Fuel/Air Flow ~750F
- Catalytic Pilot Inlet Flow ~850F

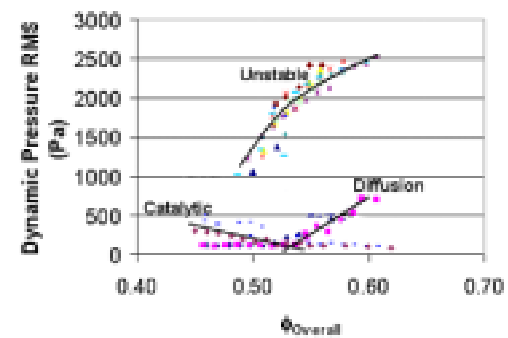
Dimensions in inches. NOT TO SCALE.

Catalytic Pilot
Comparison to LPM Pilot

Atmospheric Rig Results

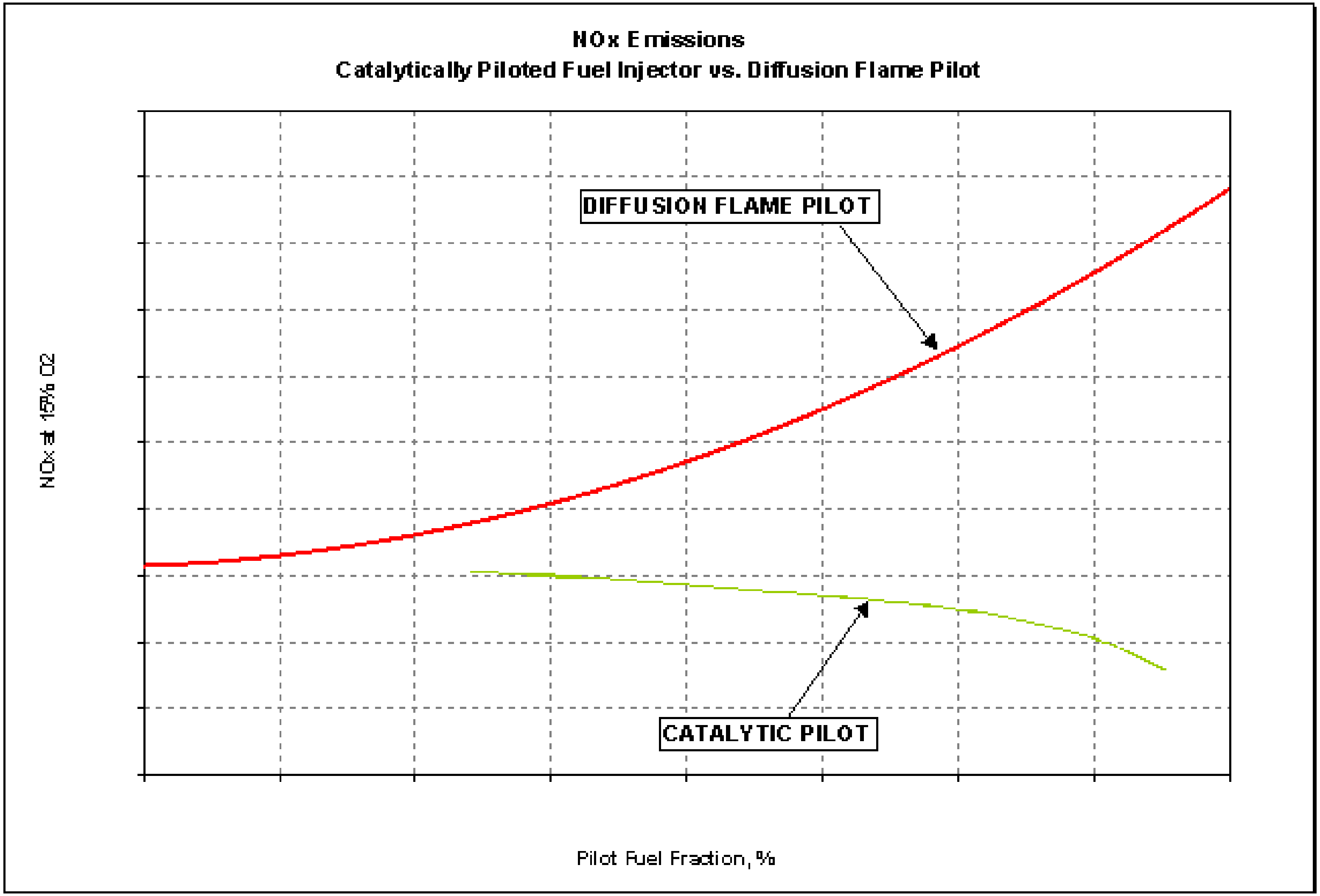






Reduced NOx	Reduced CO	Reduced Dynamics

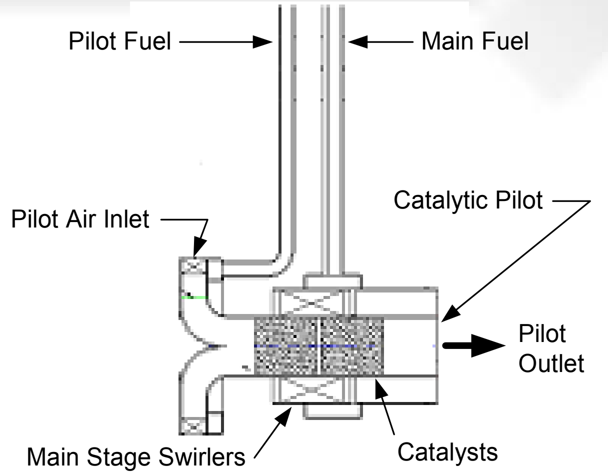
Catalytic Pilot
Full Pressure Rig Test

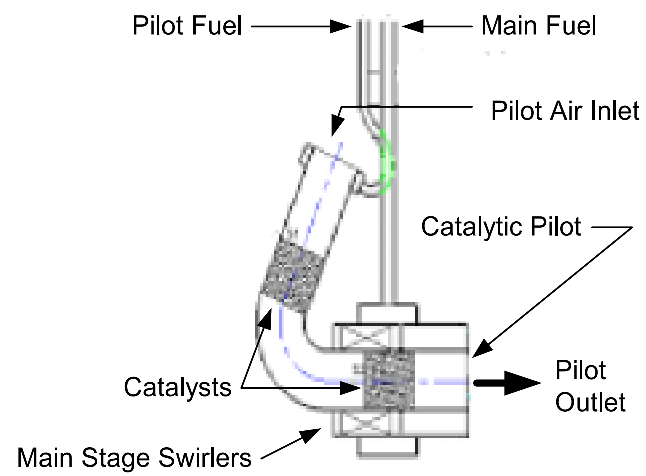


Catalytic Pilot
Final Concepts

Down Select Criteria

- Compact component envelope
- Simplicity of design and manufacture
- Minimize aerodynamic interference
- Ease of installation and removal





Catalytic Pilot

Development Status

- Completed mapping on atmospheric and full pressure rigs
- Testing indicates that a catalytic pilot can
    - Reduce NOx and CO
    - Reduce combustor dynamics over a wider range

Future Work

- Improve catalyst light-off temperature to increase range
- Demonstrate superior NOx performance in an engine test

Project Plan

- Task 1.1: Cost Reduction – Catalyst Life Extension
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- Task 2.1: Broadened Operating Range – Catalytic Secondary Burner
- Task 2.2: Broadened Operating Range – Catalytic Pilot for Lean Premix Burner
- **Task 3.1: Diesel Fuel Conversion For Xonon**

Task Objectives

- Original objectives
  - Evaluate feasibility of commercial diesel fuel conversion processes for use as source of back-up fuel in Xonon equipped gas turbine power systems
    - Investment cost target – $40/kW
    - Product composition range of converted diesel fuel
  - Test combustion catalyst performance with synthetic gas derived from commercial fuel conversion processes
- Revised objectives
  - Why objectives were revised
    - Preliminary estimates of investment costs, $250/kW, greatly exceeded target
    - Combustion of synthesis gas (original product gas) examined in another project
  - Analysis of process economics to determine cost factors and identify savings
  - Exploratory experimental project to explore alternative processing chemistry

Economics of Autothermal Reforming Fuel Processing

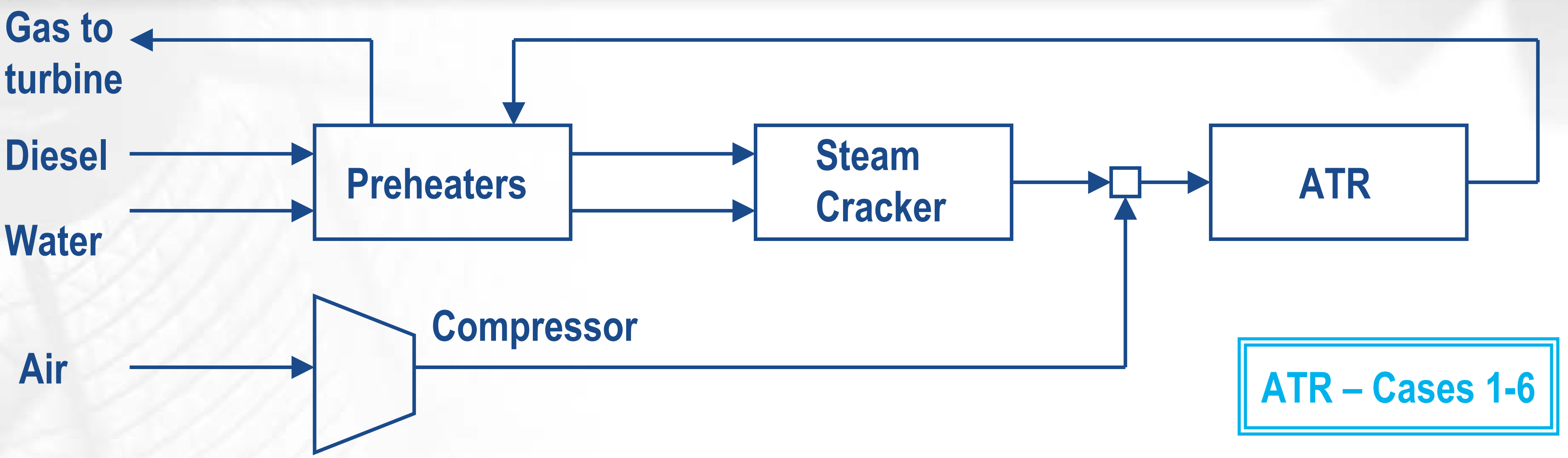
Processing design basis:

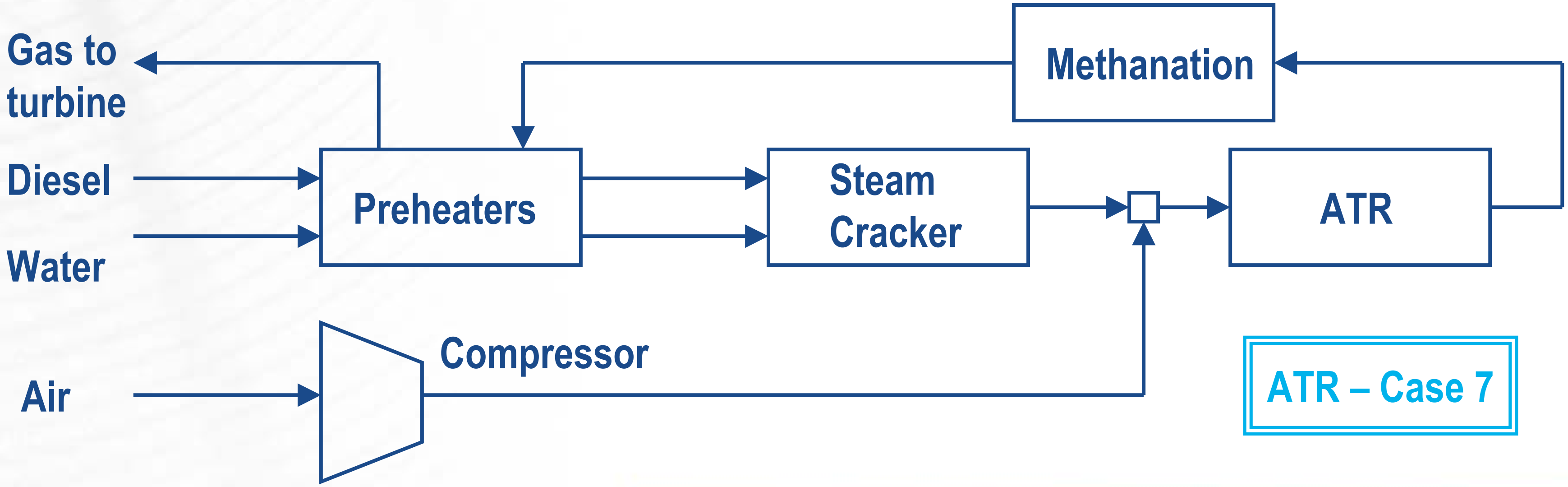
- Thermal energy production: 110-MW, 50-MW electrical at 45% efficiency
- Diesel consumption: 10-metric ton/hr
- Water feed rate: 45-metric ton/hr
- Steam/carbon ratio: 3.5:1
- Steam cracking inlet: 450°C
- Air source: 16-atm at compressor discharge
- Carbon/oxygen ratio: 2.6:1 cases 1&2; 4.5:1 cases 3-7
- ATR/Reformer Effluent: See cases

Case ID	DFC ($/kW)	Reactor Outlet Temp. (°C)	Pressure (atm)	Type Heat Exchangers	Reactor Material
Case 1 – Basecase	110.2	844	30.0	Shell/Tube	Incoloy
Case 2 – Optimized	78.9	844	30.0	PACKINOX	316SS
Case 3 – LoT, LoP-1	80.1	650	22.4	Shell/Tube	Incoloy
Case 6 – LoT, LoP-4	59.6	650	22.4	PACKINOX	316SS
Case 7 – 6+methanation	63.1	650	22.4	PACKINOX	316SS

Case1&2 – Skid-mounted base-case and optimized base-case at 30-atm; Cases3-7 – lower pressure, lower reformer temperature; Case 7 adds methanation step

Fuel Processes – Simplified Block Schematics





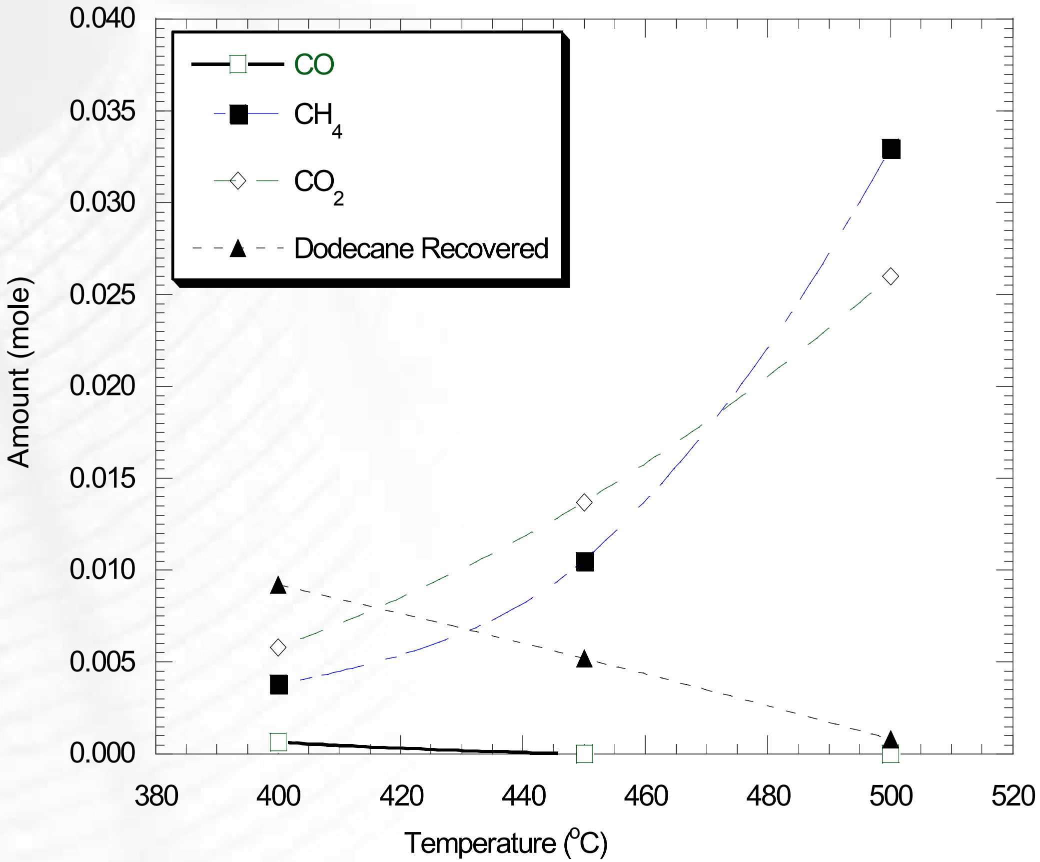
Economics of Stand-by Fuel Processing

- Conventional synthesis plant economics unattractive
  - International engineering firm and in-house estimates both showed $250/kW investment costs at the 50-MW scale
  - Modular (skid-mounted) plant construction greatly lowered investment costs
  - Reduction of temperatures and pressures offered additional savings – methane product desirable as combustion fuel but for synthesis gas
  - Best-case scenarios cost range $78 to $63/kW with increasing technological risk – still need additional processing equipment size and cost reduction
- High-pressure catalytic SNG process investigated for feasibility
  - Eliminates ATR (autothermal reformer) compressor and lowers main reactor peak temperature saving material costs despite higher pressure
  - Reactor size and catalyst durability unknown – significant risk
  - Preliminary experimental investigation of process feasibility performed in subcontract with SRI International

Exploratory High-Pressure Diesel Fuel Processing

- **Experimental Conditions**
  - Batch runs in packed tube flow reactors containing 5-gm of SiC diluent and powdered catalyst – 5 catalysts examined in 14 runs
  - Pressure range: 1500 to 3600-psia
  - Temperature range: 300-550°C
  - Liquid dodecane throughput: 3.3- to 42-liter/kg_cat/hr
  - Run duration at temperature: 20- to 45-minutes
- **Analysis**
  - Gas samples taken at 4- to 10-minute intervals; liquid collected for duration
  - GC/MS calibration for CH_4, CO, CO_2, C_2H_6 with H_2, $C_{3\text{-}4}$ hydrocarbons identified
  - Dodecane (diesel simulant) conversion determined by GC/MS of liquid
  - Intermediate liquid products not identified – determined by collected weight less dodecane

Exploratory Batch Investigation of High-Pressure Diesel Fuel Processing



Batch dodecane fuel processing results for Run #10

Primary gaseous products are CH_4, C_2H_6, and CO_2

Conversion exceeds 95-mol% at 500°C with significant production of intermediate hydrocarbons including alkenes

Small amounts of H_2 and CO detected at low temperatures

Summary of Findings

- Results of preliminary diesel gasification process development to improve economics of high pressure steam cracking are promising
  - High conversion (90%) at reasonable temperatures (500-550°C), 100-atm and 3:1 steam-to-carbon ratio with overall carbon balance ~85%
  - Primary gaseous products using dodecane as simulated diesel fuel feedstock are CH_4 and CO_2 with <5-vol% light alkanes and detectable H_2
- Economic analysis of two lowest cost processes remain above target
  - Best conventional ATR process (optimistic scenario) with reduced air flow and reactor sizes still shows investment at $63/kW, well above target ($40/kW)
  - Analysis of developmental high pressure steam cracking remains very preliminary based on uncertain mass balance and reaction rates but does project investment costs near target levels ($45-55/kW)
- Future Work
  - Determine carbon balance on process with scaled-up continuous flow reactor
  - Develop catalyst for durability and high activity in the range 450-550°C

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